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Knowledge of the Washington continental margin geology is critical in predicting acoustic response, since the region is a shallow water, bottom-interacting area. Seven geoacoustic provinces have been defined and mapped on the basis of sediment type and grain size. Each geoacoustic province has an accompanying geoacoustic model suitable for input to acoustic field models in which sediment physical properties are modeled as a function of depth.

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Geoacoustic Models: Washington State Continental Margin

Final Report

Dawn Lavoie

Seafloor Geosciences Division
Ocean Science Directorate

Foreword

This report summarizes the regional geology of the Washington continental margin. The region is divided into seven geoacoustic provinces. Each province is accompanied by a geoacoustic model that outlines the compressional and shear wave velocity as well as attenuation and density of sediment with depth. The provinces and geoacoustic models will be useful to acousticians as input for acoustic field models.

R. P. Onorati, Captain, USN
Commanding Officer, NORDA

Executive summary

Knowledge of the Washington continental margin geology is critical in predicting acoustic response, since the region is a shallow-water, bottom-interacting area. The sediments are primarily terrigenous with less than 3% calcareous constituents on the shelf and slope and less than 10% calcareous constituents in the basin areas of the region. On the Washington continental shelf, sediments form bands of sands, silty sands, silts, and muds that roughly parallel the coastline as a result of prevailing current patterns. North of the Strait of Juan de Fuca, sediment grain-size patterns are highly irregular and include significant gravel deposits.

The entire continental shelf is covered with only 150 meters and less of unconsolidated sediment. Sediment cover on the slope is more variable and ranges between a few meters on the tops of ridges to as much as 1600 meters in the valleys. The Cascadia Basin contains the thickest sediment (2500 meters) opposite the Columbia River and thins toward the Juan de Fuca Ridge.

Acoustic basement is a siltstone beneath the shelf, a mudstone beneath much of the slope, and oceanic basalt beneath the deep-sea fans and basins.

Seven geoacoustic provinces have been defined and mapped on the basis of sediment type and grain size. Each geoacoustic province has an accompanying geoacoustic model suitable for input to acoustic field models in which sediment physical properties are modeled as a function of depth.

Acknowledgments

I am indebted to J. E. Matthews of NORDA for his valuable discussions and opinions concerning geoacoustic modeling. I appreciate assistance in this cooperative effort by Drs. Paul Vidmar and Robert Koch (ARL/UT). Drs. Richard Bennett and Joseph Gettrust, and Ms. Muriel Grimm of NORDA critically reviewed the manuscript. Research was supported by NAVELEX 612, Bottom Interaction Program; Mr. Wayne Worsley, NORDA, program manager.

Contents

Illustrations

Geoacoustic models: Washington State continental margin

Introduction

This report contains a general geological description of the Washington continental margin; the continental shelf, slope, and abyssal plain between 46° and 49°N and 129° and 124°W. Descriptive maps illustrate each section and include bathymetry (Chase et al., 1981), sediment thickness, sediment type and grain size, and geoacoustic provinces. Geoacoustic models were prepared for each province as input to acoustic field models run by the Applied Research Laboratory, University of Texas, Austin (ARL/UT).

The purposes of this report are to synthesize the available data within the region, to summarize the measured and predicted values of sediment properties important in marine acoustics, and to comment on the lateral variability of the sediments. The effect of geological variability on acoustic response is discussed in a companion report being written by ARL/UT (Paul Vidmar, pers. comm.) on the Washington margin.

Geology

Setting

The geology of the Washington continental margin can be understood best within the context of the plate tectonic setting of the area. The oceanic crust in the northeast Pacific west of the Washington continental margin is divided into several plates. The two plates of interest are the Pacific and the Juan de Fuca plates, which are bounded by active spreading ridges and transform faults (Fig. 1). The Pacific plate appears to be moving northwest parallel to the San Andreas Fault (Larson et al., 1968). East of the Juan de Fuca Ridge, the Juan de Fuca plate is being subducted; oceanic crust (basalt) dips gently underneath the Washington continental slope (Barnard, 1978; Ando and Balazs, 1979). The thickness of the undeformed Cascadia Basin sediment is greatest at the base of the continental slope just west of the Columbia River, and some of this thick accumulation of Cascadia Basin turbidite and pelagic sediment apparently is being scraped off the Juan de Fuca plate as it disappears below the continental margin (Barnard, 1978; Carson et al., 1974).

The geology of the Washington continental margin has been studied by numerous investigators (Horn et al., 1971; Venkatarathnam and McManus, 1973; Barnard, 1978; Nittrouer and Sternberg, 1981; Herzer and Bornhold, 1982). Many of their conclusions are incorporated into the following description of the Washington continental margin.

The continental slope has been compressed since the Pleistocene. Deformation progressed in a westward direction, which resulted in a lower slope zone composed of north-trending, en echelon, anticlinal, mudstone and siltstone ridges (Barnard, 1978). Low areas between ridges are sediment-filled basins. Many of these basins form valleys, which drain the major canyons that incise the

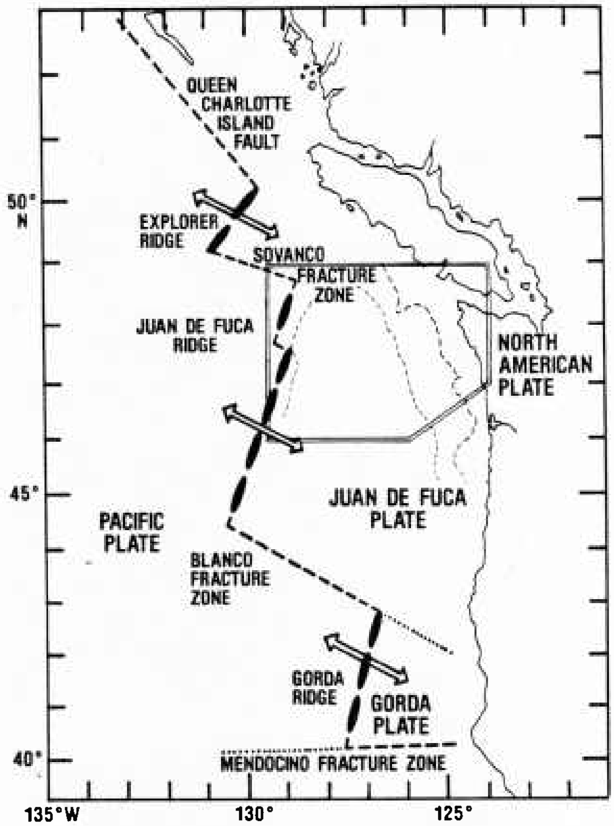

Figure 1. Arrangement of plates in the northeast Pacific (Barnard, 1978). The study area is almost entirely within the Juan de Fuca plate, which is being subducted below the Washington continental margin.

upper slope. Sediment passes through these canyons to deep sea fans in the Cascadia Basin (Fig. 2). The upper slope between submarine canyons slopes gently from the shelf break westward about 5° (Fig. 2) to the borderland.

The continental shelf of Washington is well defined by the 200-m contour within the study area. The shelf is characterized by a uniform increase in depth with increasing distance from the coast. The maximum shelf width is 55 km, and in several areas the heads of canyons have greatly narrowed the shelf. The bathymetry (Fig. 2) is generally featureless; this topography results from Columbia River sediment that has been transported northward and has covered basal irregularities (Nittrouer and Sternberg, 1981). Between 48° and 48°30′, the continental shelf is incised by the Juan de Fuca Channel which acts as a dispersion route for sediment from the Strait of Juan de Fuca to the Nitinat Fan. Both the Strait of Juan de Fuca and the Juan de Fuca Channel were formed by glacial advance. From the Juan de Fuca Channel northward, the Piedmont Glacier etched a series of troughs into tertiary bedrock, built up a complex of morainal ridges and formed an extensive outwash plain on the unglaciated shelf to the northwest. Much of this topography was leveled and smoothed, which left a flat to undulating shelf that sloped gradually seaward as sea level rose after glacial melting. However, many of the troughs were preserved either because they were still filled with ice or because the coastal system was limited in sediment volume (Herzer and Bornhold, 1982). Strong present-day currents redistribute sand and mud from the tops of the leveled moraines, and large concentrations of gravels are left behind (Fig. 3). As a result, the Canadian Shelf differs considerably in character from the Washington Shelf.

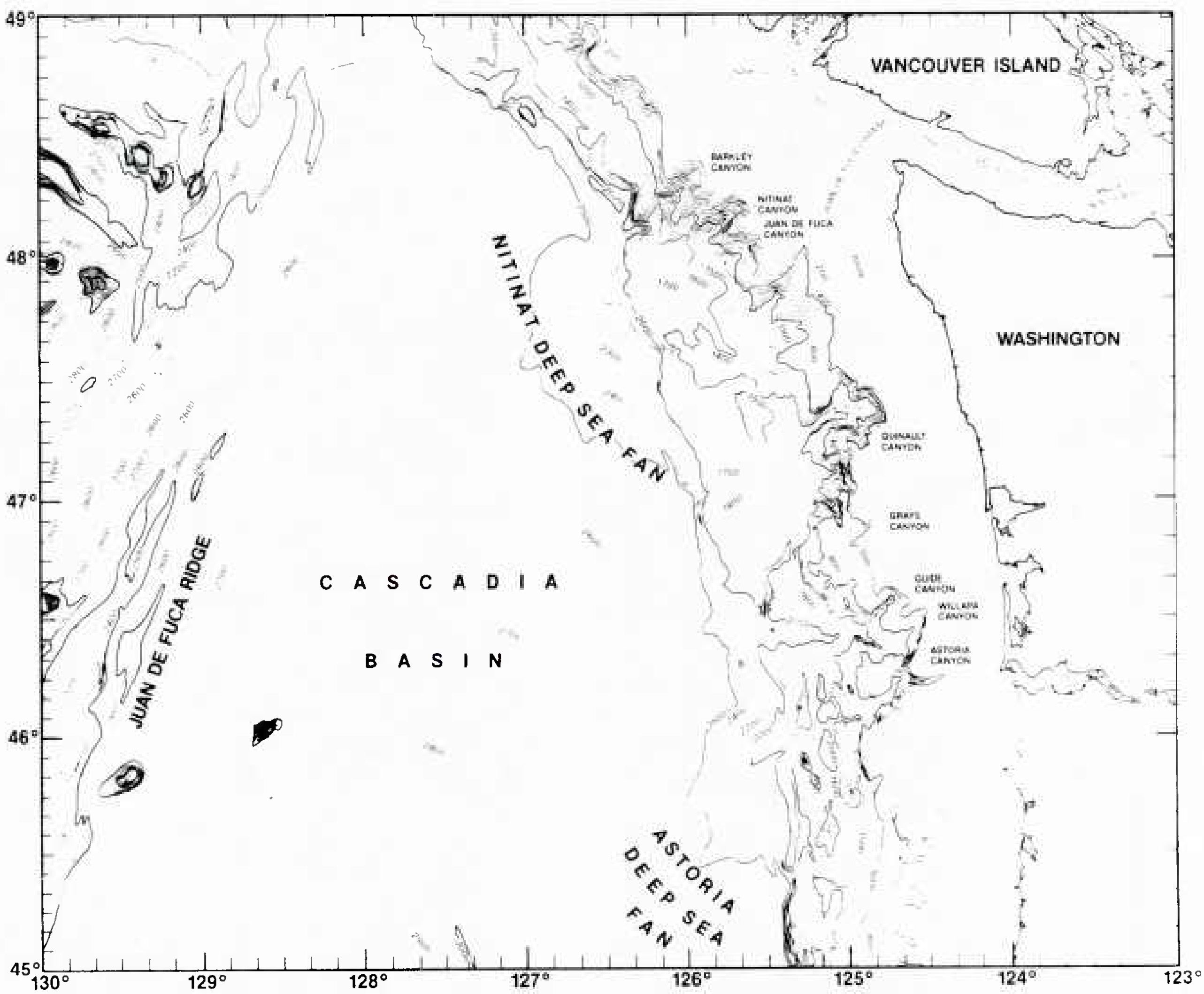

Figure 2. Bathymetry of the Washington continental margin (Chase et al., 1974).

During the lowered sea stands of the late Pleistocene, turbidity current activity was responsible for smoothing out much of the topography of the sea floor in the northeast Pacific (Horn et al., 1971). This activity created fans near the source of the turbidity flows and abyssal plains at the distal portions of the flows. Some time after the late Pleistocene, turbidity flows apparently became more restricted and were confined to channels and submarine fans (Horn et al., 1970).

The Nitinat Fan is now fed by the Juan de Fuca, the Nitinat, and the Barkley Canyons (Fig. 2). The Cascadia Basin receives sediment from the eight major channels along the Washington margin. The present basin morphology is the result of this topographic control of sediment dispersal and deposition. The topography, in turn, has been modified (uplifted) by tectonic movement near the northern Juan de Fuca Ridge (Carson, 1973). The Juan de Fuca Ridge bounds the Cascadia Basin to the west and forms the western margin of the study area (Fig. 2).

Grain size and sediment type

Washington Shelf and Slope sediment data and analyses are derived primarily from University of Washington core and grab sample data (Royse, 1964; Burnett, vols. I, II, III, 1968; Anderson and Foster, 1979; Roberts, 1974; Venkatarathnam, 19??; and Nittrouer, 1976), NAVOCEANO core data, and Canadian Shelf grain-size maps (Herzer and Bornhold, 1982). The grain-size map (Fig. 3) for the Washington Shelf was constructed using the scheme developed by Folk (1974) for gravel, sand, silt, and clay. Canadian Shelf and Slope sediment data was simplified and redrawn from Herzer and Bornhold (1982) to be consistent with the scheme used for the Washington margin.

The Columbia River is the dominant source of present-day surficial sediment on the Washington Coast (Gross et al., 1967). Terrigenous sediment is transported north from the mouth of the river by prevailing currents, and forms bands of sand, silty-sand, and silt that roughly parallel the coastline (Fig. 3). Sand is dominant on the inner shelf between the Columbia River and Cape Flattery; turbulent conditions preclude finer-grained sediments remaining for a significant length of time. Only two graveled areas are mapped on the southern Washington Shelf. Judging from their rounded nature, the gravels probably were transported and are not relict.

North of the Strait of Juan de Fuca, sediments become much less homogeneous (Fig. 3). Extremely detailed grain-

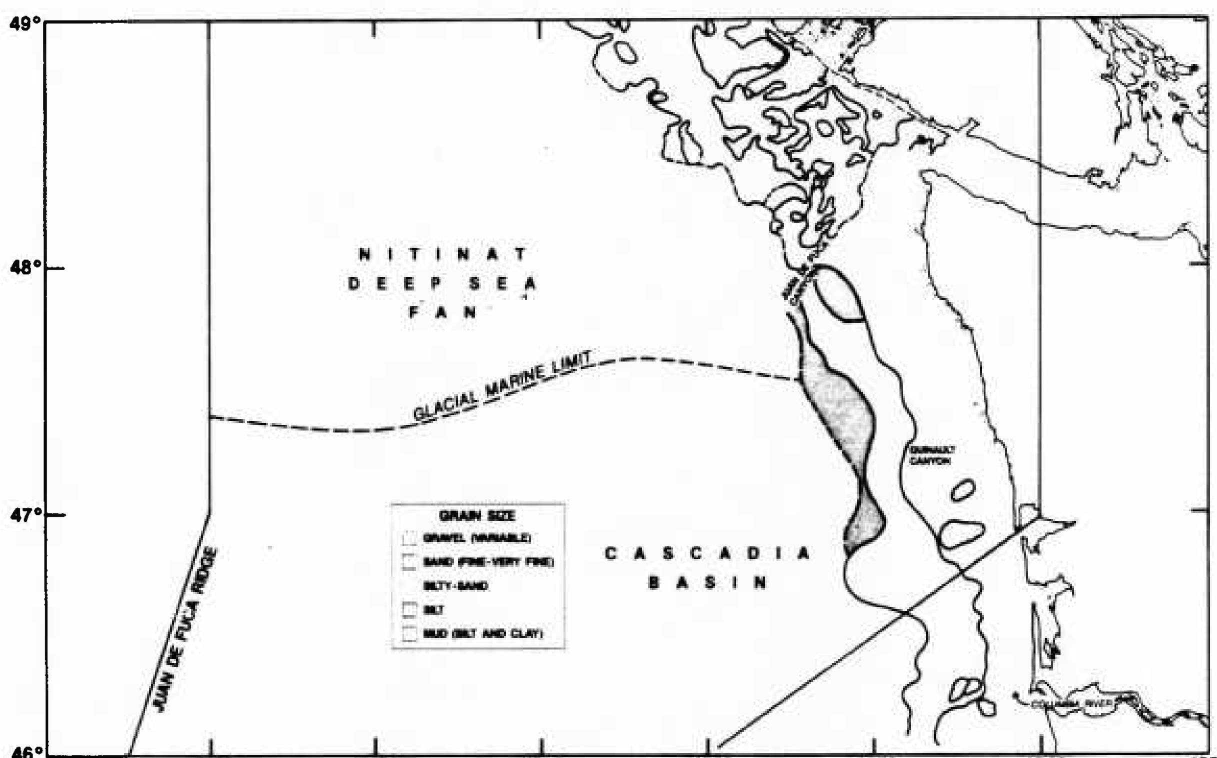

Figure 3. Grain size distribution on the Washington continental margin.

size data (Herzer and Bornhold, 1982) was combined into three major categories. Gravel is predominant on the Vancouver Shelf in depths of 70 m or less and is commonly mixed with sand and mud. Sand predominates on the outer shelf and grades from a clean sand to a muddy sand with increasing distance from the coastline. Mud is commonly found just north of the strait and just seaward of Barkley Sound, both relatively quiescent zones.

Two cores recovered from the Cascadia Basin and Nitinat Fan were analyzed at NORDA. They contained greyish-green silty clays and clayey silts. Others (Horn et al., 1971) furnished similar descriptions of basin sediments. These sediments result from turbidite deposition and generally grade upward from coarser to finer grains. Since sampling core density was not great, precise grain-size boundaries could not be defined; therefore, in this report silty clays and clayey silts are referred to as muds. The trend is for the muds to be coarser (more silty) in the portion nearer the source of turbidites and finer (more clayey) in the more distal regions near the Juan de Fuca Ridge.

Both margin and basin sediments contain small proportions of calcium carbonate sediment. The modern shelf sediment derived from the Columbia River on the Washington Shelf contains less than 1.5% carbonate. Portions of the outer shelf off Grays Canyon and all of the Vancouver Shelf that do not have a major river supplying sediment are relict sediment and contain somewhat higher proportions of carbonate. However, apart from local shell accumulations on the beaches, the only significant carbonate-rich area on the shelf is just north of the study area near the Scott Islands (50ºN) where the carbonate fraction (up to 50% and occasionally greater) is primarily of skeletal origin (Nelson and Bornhold, 1983). Basin and fan sediments contain a small (3%) fraction of pelagic carbonate.

Sediment thickness

The sediment thickness map (Fig. 4), a compilation and adaptation of sediment thickness data and maps from multiple sources (Bennett, 1969; Mayers and Bennett, 1973; Carson, 1973; Barnard, 1978; Herzer and Bornhold, 1982), has been divided into provinces for easy geoacoustic modeling. Data from Province A, the Strait of Juan de Fuca, is interpreted from seismic reflection profiles collected in the Strait by Mayers and Bennett (1973).

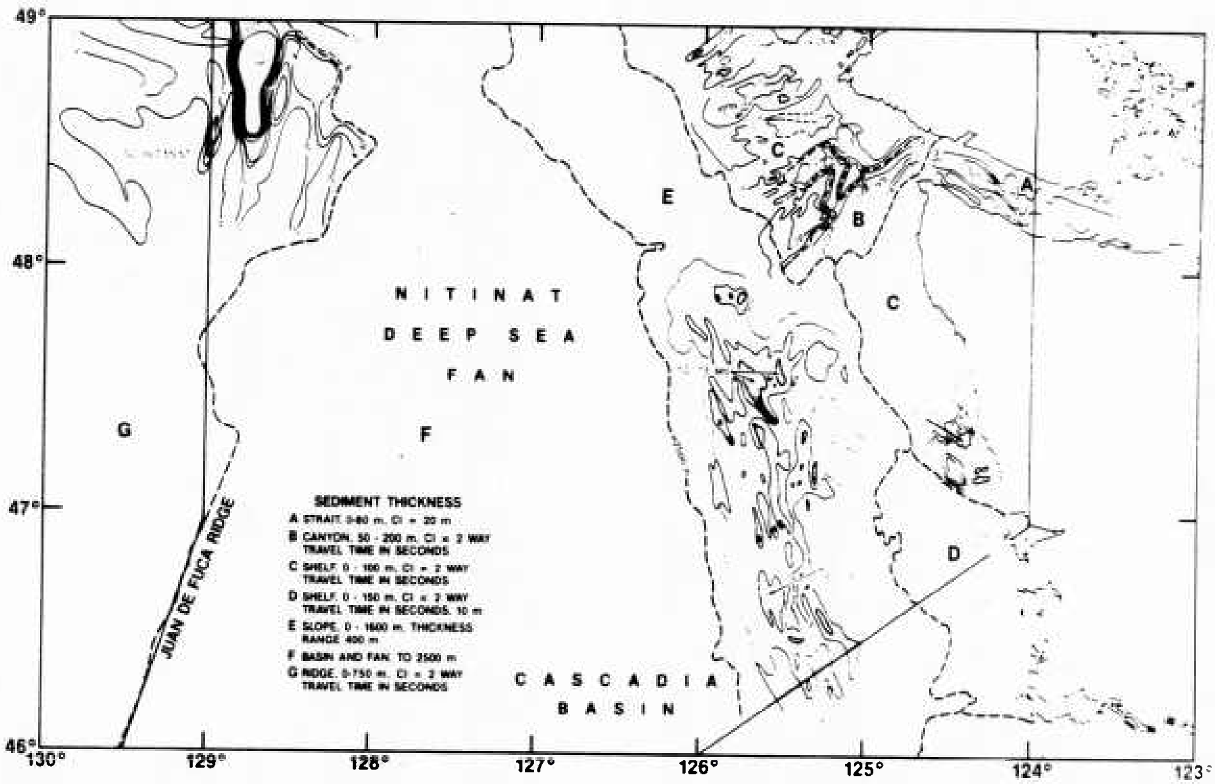

Figure 4. Sediment thickness to acoustic basement.

The strait, a trough with a U-shaped cross section carved by glacial action, contains the thickest sediment near the mouth of the strait. In the central portion, sediments thin near the northern Canadian and southern United States coastlines, which parallel the strait. Maximum sediment thickness, 80 m, is located at the mouth of the strait.

Province B includes the Juan de Fuca Channel and an adjacent thicker section of sediment outlined by the 0.23-sec (2-way travel time) contour. Contours in the channel and in Province C on the northern Canadian Shelf were derived from Herzer and Bornhold (1982). The total 2-way travel times they report (including travel time through the water) have been recontoured to show the 2-way travel times through sediment to acoustic basement (Fig. 4). Sediment thickness is left in travel times, since much of the area is graveled and only estimates of velocities and thus meters of thickness can be made.

Province B contains sand throughout the thalweg and finer grains in peripheral portions where water velocity is slower. With an average sound velocity of 1750 m/sec (Hamilton, 1980), the thickest sediment, 0.23 sec of 2-way travel time, is 201 m in the deepest portion of the channel. Directly to the north a patch of mud is resolved of equal thickness to that in the channel and is included in Province B, since normal shelf sediments are much thinner.

Province C, located north of the channel, reveals sediment thickness to be similar to that found south of the channel—generally less than 100 m of sediment. Much of northern Province C is graveled; thus, sediment thickness can only be estimated. Sediment thickness in southern Province C is contoured in only one area (Bennett, 1969) and is less than 100 m. The entire southern Province C is assumed to be thinly covered (less than 100 m), since no major rivers provide sediment. Much of the sediment on the Washington Shelf is derived from the Columbia River and travels from the river mouth to the Quinalt Canyon, where most of the sediment is funneled to the Cascadia Basin. Thus, sediment in Province D on the shelf is assumed to be as much as 50 m thicker than in Province C.

Acoustic basement underlying the continental shelf is a possibly indurated siltstone that has been compressed folded, and faulted. During a time of glaciation when sea level was lower, it also eroded and was planed to a relatively smooth surface.

The Washington Continental Slope, Province E, is a series of anticlinal ridges and valleys; sediment fills the valleys and remains relatively thin over the ridges. Thus, sediment data adapted from Barnard (1978) is mapped in gross zones of sediment thickness with a contour range of 0.5 sec of 2-way travel time, or roughly 400 m. Sediment thickness ranges from 0 m near the upper slopes to roughly 1600 m of sediment in one small ponded area (Fig. 4). Although complete data is not available, the unmapped slope region is presumed to be similar in thickness to the mapped region.

Acoustic basement underlying the continental slope is an indurated mudstone that has been compressed, folded, and faulted to a depth of at least 600 m. Since it has never been exposed to erosion, the surface remains rough.

The Nitinat Fan and Cascadia Basin, Province F, contain some of the thickest sections of sediment in the region. Sediment thickness reaches 2500 m near the base of the continental slope and thins progressively in a westward direction to the Juan de Fuca Ridge. At the Juan de Fuca Ridge, a series of ridges and valleys create a pattern of thick sediment in the valleys and thin sediment over the ridge tops. Data for this section of Province G was obtained from Carson (1973). Acoustic basement through Provinces F and G is oceanic basalt, and average basalt velocity values are used.

Geoacoustic province map and models

Seven geoacoustic provinces are shown on Figure 5. The territory within each province is composed of similar sediment type, sediment thickness, grain size, and acoustic basement. Each province has an identically numbered, accompanying model.

Province 1 falls entirely on the continental shelf and consists of fine- to very fine-layered terrigenous sands. Layers average between 3 and 30 cm and are composed of slightly varying grain sizes that average 3.5 ϕ (Burnett, 1968). A ratio of sediment velocity to bottom water velocity of 1.115 (Hamilton, 1980) was used over the entire province.

Province 2, also on the continental shelf, is graveled (greater than 30%) glacial till of varying size, and either sand or mud fills the interstitial spaces. Without sufficient data to accurately model gravel, a "best estimate" was made by assuming the mud and gravel average to equal a coarse sand. This province was modeled using a ratio of sediment velocity to bottom water of 1.201.

Province 3, on the Canadian continental shelf, is a mud province. Sediments are terrigenous silts and clays of varying proportions. A 1.014 ratio of sediment velocity to bottom-water velocity is used to characterize the mixture of silts and clays. Model 3 is extended to 150 m, the maximum sediment thickness in this province.

Province 4 is composed of a mix of sediments with an average grain size of 5.5 ϕ. Therefore, this zone is referred

to as a zone of slope silts. The velocity ratio of sediment to bottom water is 1.057. Depth to acoustic basement is variable; thus, the model extends to 800 m. Depending on actual site location, the model data can be stopped at a shallower depth.

Province 5, also on the slope, is a zone of terrigenous, silty sands. Sediment thickness in this zone is also variable—thick in the valleys and thin on the ridge tops. An average velocity ratio of sediment to bottom water of 1.078 is used. Acoustic basement is a zone of compressed folded and faulted siltstone.

Province 6, on the continental slope, is a zone of muds, mixed silts, and clays of variable proportions. An average ratio of sediment velocity to bottom water velocity is 1.014; thus, model 3 is appropriate for this province. Acoustic basement, however, is a consolidated mudstone that is folded and faulted.

Province 7, the Cascadia Basin and Nitinat Fan, is composed entirely of turbidite sediments with individual turbidite sequences less than a meter in thickness. These grey-green turbidites are bedded and graded silty clays. Since sediments become finer toward the west as distance from the source increases, they are modeled with a velocity ratio of 0.994. Acoustic basement is oceanic basalt. Average values from Hamilton (1980) are used.

Sediment variability

The complex regional geology and the deformation of acoustic basement underlying the Washington slope are depicted in the lateral variability of the surficial sediments. Although sediments are primarily terrigenous, grain size varies from gravels (dominant north of the Strait of Juan de Fuca) to clays and silts (dominant in the basinal areas). Physical property characteristics vary with grain size; thus, with each change in grain size the compressional and shear wave velocity and attenuation change. These velocity and attenuation changes in shallow water ultimately affect acoustic response. The variability of surficial sediments is especially apparent north of the strait where the smoothing influence of Columbia River sedimentation is not observed. Relict sands and gravels (glacial till) remain in place, untransported by present-day currents and uncovered because of low sedimentation rates. Low current areas account for the presence of muds (silts and clays), which are often found close to glacial tillites. At the same

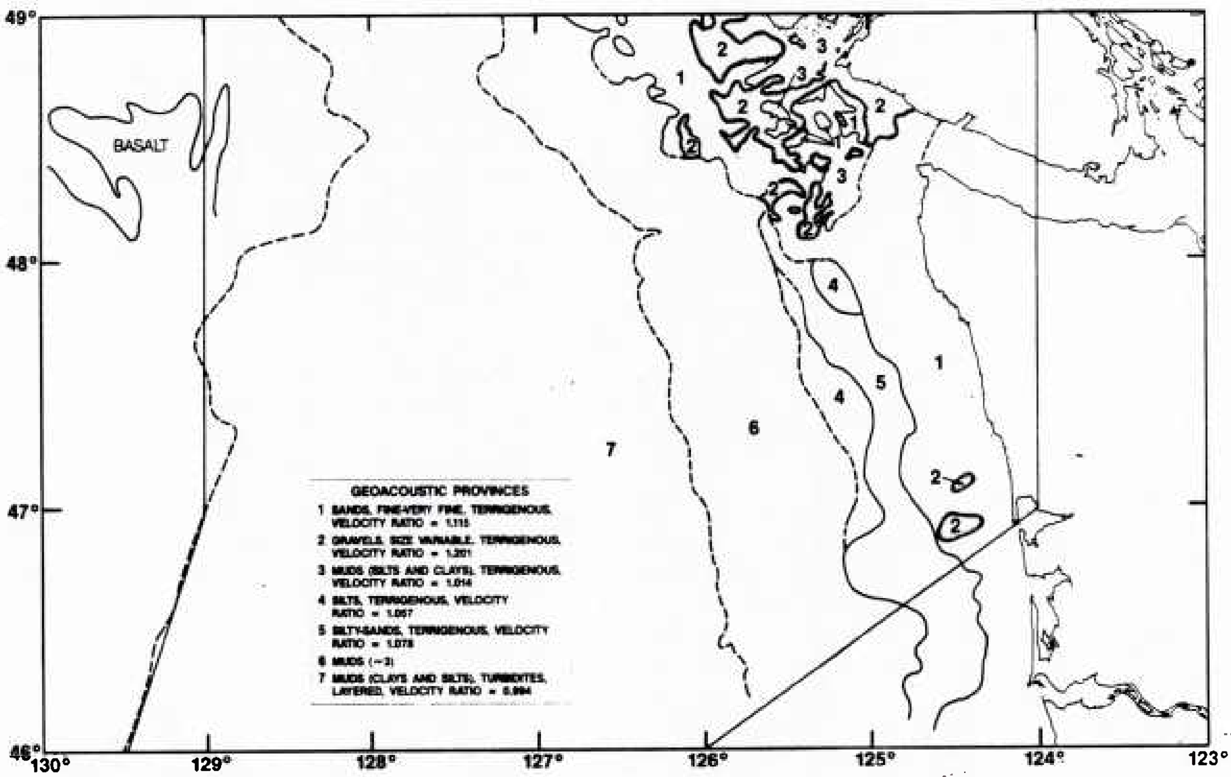

Figure 5. Geoacoustic Province Map.

time, the gravels do not persist with depth; short cores reveal sands and silts present below the gravels (Herzer and Bornhold, 1982). Basement is fairly level on the shelf as a result of the erosional episodes during the Pleistocene. With depth, however, gentle anticlinal ridges can be observed from seismic records.

Adjacent to the shelf, acoustic basement underlying the slope is extremely rough, folded, faulted, and compressed; thus, its upper surface is impossible to map. A surface zone of highly fractured and compressed siltstone and mudstone basement is evident and, as a result, sediment thickness on the slope is highly variable. Transported sediment fills the low areas after leaving the high areas thinly veneered with sediment. Variability on the slope region thus consists of basement roughness influencing sediment thickness.

The Cascadia Basin, with its thick accumulation of sediment (turbidite deposited), is the most homogeneous section of this area, so sediment variation with lateral extent is the most predictable and easily modeled. Sediment variation occurs vertically and by virtue of its deposition mode can be modeled accurately in specific locations.

Washington Coast Province 1

	Depth (m)	Vp (m/sec)	Vs (m/sec)	Kp (dB/m/kHz)	Ks (dB/m/kHz)	Density (g/cc)
Sea Surface Bottom Water	50-200	1483				
	0	1654	55	0.37	13.2	1.9
	5	1772	201	0.30	10.7	1.9
	10	1791	244	0.27	9.8	1.9
	15	1802	273	0.26	9.3	1.9
very	20	1810	296	0.25	8.9	1.9
fine	25	1816	315	0.25	8.9	1.9
sands	50	1835	383	0.22	7.8	1.9
	75	1846	429	0.21	7.5	1.9
	100	1854	465	0.21	7.5	1.9
	125	1860	495	0.20	7.1	1.9
	150	1865	521	0.19	6.8	1.9
Acoustic Basement (Siltstone)		3000	1500	0.03	3.0	2.54

Notes:

Province 1 consists of fine and very fine terrigenous sands. Grain-size measurements were made from several NORDA cores and many University of Washington cores (Burnett, 1968). Shelf sediments are layered; layers average between 3 and 30 cm and are composed of slightly varying phi sizes within the sand-size range. Velocity ratio of sediment to bottom water (1.115) is an average value for sands (3.5 ϕ) taken from Hamilton (1980).

Bottom-water velocity is highly variable in the upper 200 m. An average value of velocities between 50 and 200 m was used. Data was compiled by Soileau and Bucca (1984).

Compressional wave velocity (Vp) was calculated using $Vp = KZ^{.015}$ (Hamilton, 1980). K is a constant (1730 m/sec) derived by using a calculated initial velocity of 1654 m/sec. A measured initial velocity of 1637 m/sec was felt to be low. Z is depth in meters.

Shear wave velocity (Vs) was calculated using $Vs = 128Z^{.28}$ from in situ data (Hamilton, 1980). Z is depth in meters.

Initial compressional wave attenuation Kp0 is estimated to be 0.37 dB/m/kHz. $Kp(Z) = [Kp0 - 0.214/0.236] [0.45Z^{-1/6} - (0.214 - 0.00014Z)] + 0.214 - 0.00014Z$. Z is depth in meters. The regression equation is derived from data presented by Hamilton (1980).

Shear wave attenuation is assumed to be proportional to compressional wave attenuation: $Ks(depth) = Kp(depth) (Ks0/Kp0)$.

The measured density of shelf sands is approximately 1.9 g/cc (NORDA cores) and does not change over 150 m of sediment thickness.

Acoustic basement is a siltstone; average values are estimated from Clark (1966).

Washington Coast Province 2

	Depth (m)	Vp (m/sec)	Vs (m/sec)	Kp (dB/m/kHz)	Ks (dB/m/kHz)	Density (g/cc)
Sea Surface Bottom Water	0-100	1486 (variable)				
	0	1783	41.0	0.23	13.2	2.03
	5	1910	172.4	0.35	10.9	2.03
	10	1930	214.0	0.27	10.2	2.03
gravel	15	1942	242.9	0.25	9.4	2.03
modeled	20	1951	265.7	0.25	9.4	2.03
as	25	1957	284.8	0.24	9.1	2.03
coarse	50	1978	353.6	0.22	8.3	2.03
sand	75	1990	401.3	0.21	7.9	2.03
	100	1998	438.9	0.20	7.5	2.03
	125	2005	470.6	0.20	7.5	2.03
	150	2011	498.1	0.19	7.2	2.03
Acoustic Basement (Siltstone)		3000	1500.0	0.03	3.0	2.54

Notes:

Province 2 is composed of shelf gravels (greater than 30%) that are primarily glacial till. Some data was analyzed by the Canadians (Herzer and Bornhold, 1982), and raw data was provided by the University of Washington (Nittrouer, 1976; Roberts, 1974; Burnett, 1968). Since knowledge of the effects of gravel on acoustic problems is sparse, and since measurements of velocities and attenuations on gravels are also scarce, this province has been modeled as a coarse sand with an approximate velocity ratio of 1.201.

Bottom water velocity in the first 100 m of water is highly variable; an average yearly value of 1486 m/sec was used.

$Vp = KZ^{.015}$, where K is a constant (1865 m/sec) and Z is depth in meters (Hamilton, 1980).

$Vs = 104.33Z^{.312}$ where Z is depth in meters. The regression equation is derived from data on three kinds of sands (fine, medium, and coarse), based on data from Ohta and Goto (1978).

An initial Kp was derived from Hamilton data (1980). $Kp(Z) = [Kp0^{-1/6} - 0.214/0.236]\ [0.45Z^{-1/6} - (0.214 - 0.00014Z)] + 0.214 - 0.00014Z.$

Ks is assumed to be proportional to Kp with depth and is calculated accordingly.

Density is estimated to be 2.03 g/cc throughout the top 150 m of sediment cover.

Acoustic basement is the same as in Province 1.

Washington Coast Province 3

	Depth (m)	Vp (m/sec)	Vs (m/sec)	Kp (dB/m/kHz)	Ks (dB/m/kHz)	Density (g/cc)
Sea Surface Bottom Water	1-100	1486				
	0	1507	96	0.090	17.3	1.49
	5	1514	123	0.092	17.7	1.50
	10	1520	147	0.095	18.2	1.50
	15	1526	170	0.097	18.6	1.51
clayey	20	1533	197	0.099	19.0	1.52
silts	25	1539	220	0.101	19.4	1.52
	50	1570	300	0.110	21.1	1.56
	75	1601	335	0.118	22.7	1.59
	100	1630	368	0.125	24.0	1.62
	125	1659	400	0.130	25.0	1.65
	150	1687	412	0.134	25.8	1.69
Acoustic Basement (Siltstone)		3000	1500	0.03	3.00	2.54

Notes:

Province 3 shelf sediments are muds, a combination of silts and clays, modeled here as clayey silts. A calculatea velocity ratio of 1.014 was taken from Hamilton (1980). Data was from the same sources used in Provinces 1 and 2.

Bottom water velocity is highly variable in the upper 100 m of water. A yearly average of 1486 m/sec was used. A more appropriate value may need to be substituted if a particular site (depth) and time of year is selected.

Initial sediment compressional wave velocity ($Vp0$) is calculated to be 1507 m/sec and is comparable to measured values obtained from cores. $Vp = Vp0 + 1.304Z - 0.741Z^2 + 0.257Z^3$ where Z is depth in kilometers and $Vp0$ is entered as kilometers/second (Hamilton, 1980).

Shear wave velocities were determined using a range of equations (Hamilton, 1980):

$Vs = 3.884Vp - 5.757$ for $Vp = 1.512$ *to* 1.555

$Vs = 1.137Vp - 1.485$ for $Vp = 1.555$ *to* 1.650

For $Vp = 1.650$ *to* 2.150 $\quad Vs = 0.991 - 1.136Vp + 0.47Vp^2$

An initial compressional wave attenuation ($Kp0$) was estimated to be 0.090 from data tabulated by Hamilton (1980). Kp as a function of depth was calculated: $Kp(Z) = 0.214 - 0.00014Z - (0.2140Kp0)e^{-Z/200}$. This regression equation was adapted from sediment attenuation versus depth plotted by Hamilton (1980).

Shear wave attenuation is assumed to be proportional to compressional wave attenuation and is calculated accordingly.

Density was calculated $D = 1.49 + 1.395(Z) - 0.617Z^2$ (Hamilton, 1976). This was correlated with porosity (70%) and seems to be in agreement with measured values.

Acoustic basement is siltstone. The same values are used as in Provinces 1 and 2.

Washington Coast Province 4

	Depth (m)	Vp (m/sec)	Vs (m/sec)	Kp (dB/m/kHz)	Ks (dB/m/kHz)	Density (g/cc)
Sea Surface Bottom Water	300-1200	1480				
	0	1564	293	0.265	13.4	1.59
	5	1571	301	0.239	11.9	1.59
	10	1577	308	0.231	11.5	1.60
	15	1583	315	0.226	11.3	1.61
	20	1590	323	0.223	11.1	1.61
	25	1596	330	0.221	11.0	1.62
	50	1627	365	0.212	10.6	1.66
	75	1657	399	0.206	10.3	1.69
silts	100	1687	412	0.202	10.1	1.72
	125	1716	426	0.201	9.9	1.76
	150	1744	439	0.193	9.6	1.79
	200	1797	467	0.186	9.4	1.85
	250	1848	497	0.179	9.1	1.91
	300	1895	526	0.172	8.7	1.96
	400	1983	586	0.158	8.0	2.06
	600	2135	708	0.130	6.6	2.23
	800	2265	829	0.102	5.2	2.38
Acoustic Basement (Mudstone)						

Notes:

Province 4 is composed of a mix of sediments with an average grain size of 5.5 ϕ. Therefore, this province is referred to as a zone of slope silts. The velocity ratio is 1.057.

Bottom water velocities are fairly stable between 300 and 1200 m of water depth (Soileau and Bucca, 1984). An average bottom water velocity of 1480 m/sec is assumed to be representative of this province.

Initial Vp = 1564 m/sec. $Vp(Z) = Vp(0) + 1.304Z - 0.741Z^2 + 0.257Z^3$ where Z is depth in kilometers

$Vs = 3.884Vp - 5.757$ for $Vp = 1.512$ *to* 1.555 *km/sec.*

$Vs = 1.137Vp - 1.485$ for $Vp = 1.555$ *to* 1.650 *km/sec.*

$Vs = 0.991 - 1.136Vp + 0.47Vp^2$ for $Vp = 1.650$ *to* 2.150 *km/sec.*

$Vs = 0.78 - 0.962$ for $Vp = >2.150$ *km/sec.*

$Kp0 = 0.265$ *dB/m/kHz.* $Kp(Z) = [Kp0 - 0.214/0.236]\,[0.45Z^{-1/6} - (0.214 - 0.00014Z)] + 0.214 - 0.00014Z$. The regression equation was derived from data presented by Hamilton (1980).

Ks is assumed to be proportional to *Kp* over depth and is calculated accordingly (Hamilton, 1978): $Density = 1.135Vp - 0.19$.

Acoustic basement is on the Washington Continental Slope in a region or zone of compressed, folded and faulted, possibly lithified siltstone and mudstone. It is not possible to pick a continuous reflector as acoustic basement; therefore, no values are assigned.

Washington Coast Province 5

	Depth (m)	Vp (m/sec)	Vs (m/sec)	Kp (dB/m/kHz)	Ks (dB/m/kHz)	Density (g/cc)
Sea Surface Bottom Water	100-1000	1478				
	0	1593	55	0.35	13.3	1.70
	5	1707	201	0.29	11.0	1.71
	10	1725	244	0.27	10.3	1.72
	15	1735	273	0.25	9.5	1.72
	20	1743	296	0.25	9.5	1.73
	25	1748	315	0.24	9.1	1.73
silty	50	1767	383	0.22	8.4	1.77
sands	75	1778	429	0.21	8.0	1.80
	100	1785	465	0.20	7.6	1.83
	125	1791	495	0.20	7.6	1.86
	150	1796	521	0.19	7.2	1.90
	200	1804	564	0.19	7.2	1.95
	300	1815	632	0.17	6.5	2.06
	400	1823	685	0.17	6.5	2.16
Acoustic Basement (Mudstone)						

Notes:

Province 5 is a region of terrigenous silty sands that ranges between 0 and 400 m thick on the Washington Continental Slope. Sediment is thin on the tops of folds and thick in the valleys between ridges. An average velocity ratio of 1.078 is used.

Bottom water velocity is variable over this water depth. An average velocity of 1478 m/sec was chosen as representative; however, more specific values may be used according to the particular site chosen.

An initial compressional wave velocity ($Vp0$) was calculated to be 1593 m/sec. $Vp(Z)$ was calculated (Hamilton 1980): $Vp(Z) = KZ^{.015}$. K is a constant calculated to be 1666 m/sec and Z is depth in meters.

$Vs(Z)$ was calculated using $Vs = 128Z^{.028}$ where Z is depth in meters (Hamilton, 1980).

$Kp(0)$ was calculated from a measured porosity of 56%.

$Kp(Z) = [Kp0 - 0.214/0.236][0.45Z^{-1/6} - (0.214 - 0.00014Z)] + 0.214 - 0.00014Z$ to a depth of 200 m. Below 200 m, $Kp(Z) = 0.45Z^{-1/6}$.

Ks is assumed to be proportional to Kp with depth.

Density was calculated using Hamilton's (1976) equation: $D = 1.70 + 1.395(Z) - 0.617(Z)$

Acoustic basement is the same as that of Province 4.

Washington Coast Province 6

	Depth (m)	Vp (m/sec)	Vs (m/sec)	Kp (dB/m/kHz)	Ks (dB/m/kHz)	Density (g/cc)
Sea Surface Bottom Water	1000-2500	1485				
	0	1506	92	0.080	17.0	1.45
	5	1512	116	0.083	17.6	1.46
	10	1519	143	0.085	18.1	1.46
	15	1526	170	0.088	18.7	1.47
	20	1532	193	0.090	19.1	1.48
	25	1538	217	0.092	19.6	1.48
	50	1569	299	0.103	21.9	1.52
clayey	75	1600	334	0.111	23.6	1.55
silt	100	1629	367	0.119	25.3	1.58
	150	1686	412	0.130	27.6	1.65
	200	1739	437	0.137	29.1	1.70
	300	1837	490	0.142	30.2	1.81
	400	1925	546	0.140	29.8	1.91
	500	2005	603	0.133	28.3	1.99
	600	2077	659	0.130	27.6	2.06
	800	2207	759	0.102	21.7	2.17
	1000	2326	852	0.074	15.7	2.23
Acoustic Basement (variable)						

Notes:

Province 6 is located on the Washington Continental Slope. Sediments are lutites (muds). The velocity ratio used is 1.014 (Hamilton, 1980), which agrees well with measured velocity ratios from NORDA cores.

$Vp(Z) = Vp0 + 1.304Z - 0.741Z^2 + 0.257Z^3$, where Z is depth in kilometers (Hamilton, 1980).

$Vs(Z) = 3.884Vp - 5.757$ for $Vp = 1.512$ to 1.555 *km/sec.*

$Vs(Z) = 1.137Vp - 1.485$ for $Vp = 1.555$ to 1.650 *km/sec.*

$Vs(Z) = 0.991 - 1.136Vp + 0.47Vp^2$ for $Vp = 1.650$ to 2.150 *km/sec.*

$Vs(Z) = 0.78Vp - 0.962$ for $Vp > 2.150$ *km/sec.*

An initial $Kp0$ of 0.08 was derived from a measured porosity of 78%.

$Kp(Z) = 0.214 - 0.00014Z - (0.214 - Kp0)e^{-Z/200}$ to 450 *m.*

$Kp(Z) = 0.214 - 0.00014Z$ below 450 m where Z is depth in kilometers. This regression equation was derived from data presented by Hamilton (1980).

Ks is assumed to be proportional to Kp with depth and is calculated accordingly.

$Density = 1.45 + 1.395Z - 0.617Z^2$, where Z is depth in kilometers (Hamilton, 1976).

Acoustic basement is the same as in Province 4.

Washington Coast Province 7

	Depth (m)	Vp (m/sec)	Vs (m/sec)	Kp (dB/m/kHz)	Ks (dB/m/kHz)	Density (g/cc)
Sea Surface Bottom Water	>2500	1498				
	0	1489	26.3	0.065	17.3	1.42
	5	1496	53.5	0.066	17.6	1.36
	10	1502	76.8	0.071	18.9	1.36
	15	1508	100.0	0.074	19.7	1.37
	20	1515	127.3	0.076	20.2	1.38
silty	25	1521	150.6	0.079	21.0	1.38
clays	50	1552	271.0	0.091	24.2	1.42
	75	1583	314.9	0.100	26.6	1.45
	100	1612	347.8	0.110	29.3	1.60
	200	1722	428.5	0.131	34.9	1.67
	300	1820	480.3	0.139	37.0	1.71
	400	1908	534.5	0.138	36.7	1.81
sed.	600	2060	645.3	0.130	34.6	1.96
rock	800	2189	745.4	0.123	32.7	2.07
	1000	2309	839.0	0.116	30.9	2.13
Acoustic Basement (Basalt)		5300	2680	0.02	0.07	2.7

Notes:

Sediments in Province 7 are turbidites with layers less than a meter thick. These turbidites are grey-green, bedded, graded, silty clays with an approximate velocity ratio of 0.994. Sediments are up to 2000 m in thickness near the base of the continental slope, thinning in the direction of the Juan de Fuca Ridge. Some areas of the ridge are bare of sediment entirely.

$Vp(Z) = Vp0 + 1.304Z - 0.741Z^2 + 0.257Z^3$ where Z is depth in kilometers (Hamilton, 1980).

Vs is computed as in Province 6.

$Kp(Z) = 0.214 - 0.00014Z - (0.214 - Kp0)e^{-2/200}$ to 450 m. Below 450 meters, $Kp(Z) = 0.214 - 0.00014Z$. The regression equations are derived from data presented by Hamilton (1980).

Ks is assumed to be proportional to Kp with depth. An initial *Ks* was assumed from data presented by Hamilton (1980).

Density with depth was calculated (Hamilton, 1978): $D(Z) = D(0) + 1.395Z - 0.617Z^2$.

Acoustic basement is oceanic basalt; average values for basalt are listed.

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